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Flexible facing systems for surficial slope stabilisation: a literature review

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Abstract

Flexible facing systems, the main element of which is a pinned net, are widely used to stabilise ground layers on slopes. Today, this technique benefits from decades of successful experience. The optimisation of their design has motivated a great deal of research, based on experiments and numerical modelling, particularly in recent years. This literature review first gives a synthetic overview of the available analytical design methods, before presenting the various research studies that have been carried out on flexible facing systems. The response of flexible facing systems is then discussed in a didactic manner, focusing on the membrane and paying particular attention to the mechanisms and parameters that influence this response. The relevance of current practices in terms of component characterisation tests and analytical approaches to design is then discussed. Finally, the latest research is presented and the best design criteria are discussed.

Keywords: slope failure, protection structure, design, analytical models

1 Introduction

The stability of layers of soil or weathered rock masses on natural and new cut slopes may be efficiently improved by flexible facing systems (FFS). FFS consist of a membrane anchored to the stable substratum thanks to nails and complemented with ropes and nail plates as illustrated in Fig. 1. FFS may also integrate other components such as connection members, secondary membrane or short intermediate nails. The membrane generally consists of hexagonal wire mesh, rhomboidal mesh or a cable net. Secondary membranes, made of polymeric or natural materials, are often placed under the main membrane to contain and protect the soil surface from erosion (Castanon-Jano et al, 2021). Ropes may be used at the side of the membrane (boundary ropes) or above the membrane to prevent it from excessive deformation (reinforcement ropes). Some commercially available products consist of a membrane combined with reinforcement ropes. The membrane and ropes are connected to steel bars, i.e. nails, passing through the unstable layer and secured in the stable substratum beneath. Each nail is equipped with a nut and a nail plate at its free end. The nail plate secures the membrane. In the field, nails are arranged according to either a rectangular or a rhomboidal (diamond) pattern. The latter pattern corresponds to a staggered formation where horizontal nail rows are alternatively shifted by half the horizontal distance between two nails as illustrated in Fig. 1. FFS may stabilise ground layers with thickness up to 3 m (Blanco-Fernandez et al, 2011) and inclined by up to 70° (British standard institution, 2011). FFS may be designed as passive or active systems. In this latter case, the membrane generates on the ground layer a confining stress in a 10-20 kPa typical range (Justo et al, 2014).

A great deal of research has been carried out over the last few decades to propose and improve design methods for FFS, and in particular for their main components, i.e. membranes and nails. These works were based on lab and large-scale experiments as well as on numerical modelling, for addressing the mechanical response of whole or part

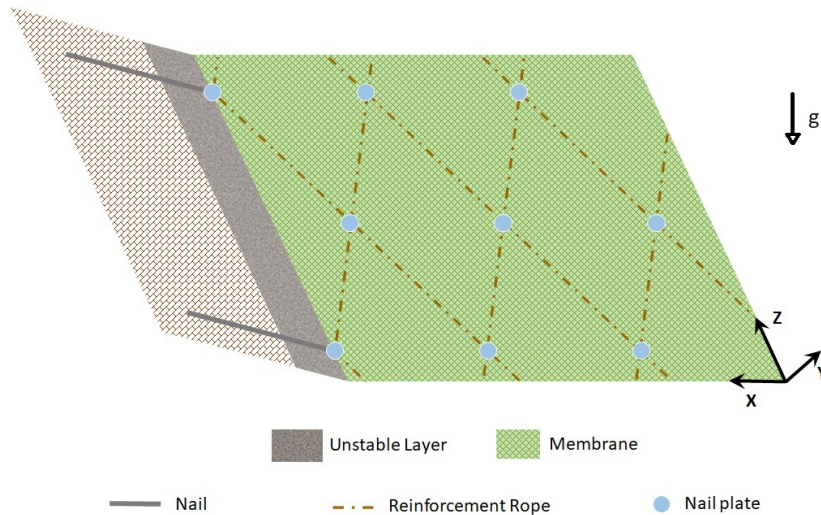


Fig. 1 Schematic of a FFS portion with reinforcement ropes, where the layout of both the nails and reinforcement ropes follow a rhomboidal pattern.

of the FFS, sometimes including the ground layer. Research were carried out worldwide (in Australia, Canada, Italy, Poland, Spain, Switzerland and the USA). Significant contribution to research was made by manufacturers (namely Brugg, Maccaferri and Iberotalud) on their own or in collaboration with some public institutes, in particular in view of proposing design methods of their products.

This literature review addresses the design of FFS based on the current state-of-the-art established considering publicly available documents published over the past twenty years and written in English. This document mainly considers references dealing with the stabilisation of unstable layers made from soil or weathered rock masses. It also refers to references dealing with the stabilisation of rock blocks when these illustrate some specific points which are believed to apply to the case of unstable layers. Similar systems used in tunnelling applications are not covered. In addition, very little attention is paid to other aspects of FFS design mentioned or dealt with in other documents. This concerns the design of nails and nail plates (Shu et al, 2005a; EOTA, 2016; Pol and Gabrieli, 2021, 2022), the loads induced by ice and snow deposits (Shu et al, 2005b), seismic actions (Maccaferri, 2021b), surcharge on the crest, water flow

in the ground layer (Da Costa and Sagasetta, 2010; Jimenez Fernandez et al, 2021), presence of vegetation or roots (British standard institution, 2011), ageing and safety factors to consider (Da Costa and Sagasetta, 2010; Maccaferri, 2021b).

Basically, the performance of FFS is mainly related to the confining effect provided by the membrane to the unstable layer. In the principle the FFS is designed to exert on the unstable layer a force balancing the excess in driving force, to prevent from layer failure or displacement. The loading exerted by the unstable layer on the membrane transmits to the ropes, nail plates and nails towards the stable substratum and all these components require a proper design. As schematically described in Fig. 2, FFS used to stabilise ground layers on slopes may undergo different types of loading depending on the ground type, ground characteristics evolution, etc. In this context, the most important characteristics of FFS to consider are (i) puncturing resistance on the upper edge of the nail plate and (ii) shear resistance at the contact between the membrane and the nail plate. These characteristics are associated with the two main membrane failure mechanisms observed on-site and illustrated in Fig. 3 (Muhunthan et al, 2005; Bucher et al, 2016). It is generally considered that the lower the deflection of the membrane for reaching the required confining stress to stabilise the ground, the better the design (Bucher et al, 2016). From this view point, active systems appear advantageous over passive ones. Such an active behaviour is obtained either prestressing the nails or the ropes (Justo et al, 2014). Even though FFS now benefit from significant research and decades of successful applications in various contexts (Flum et al, 2004; Farrand and Teen, 2008; Justo et al, 2014; Lopamudra and Gourango, 2016/11; Jackson and Buechi, 2017) and are covered by one British standard and one European Assessment document (British standard institution, 2011; EOTA, 2016), a critical review of existing design methods and current knowledge raises questions suggesting possible improvement tracks for their global design.

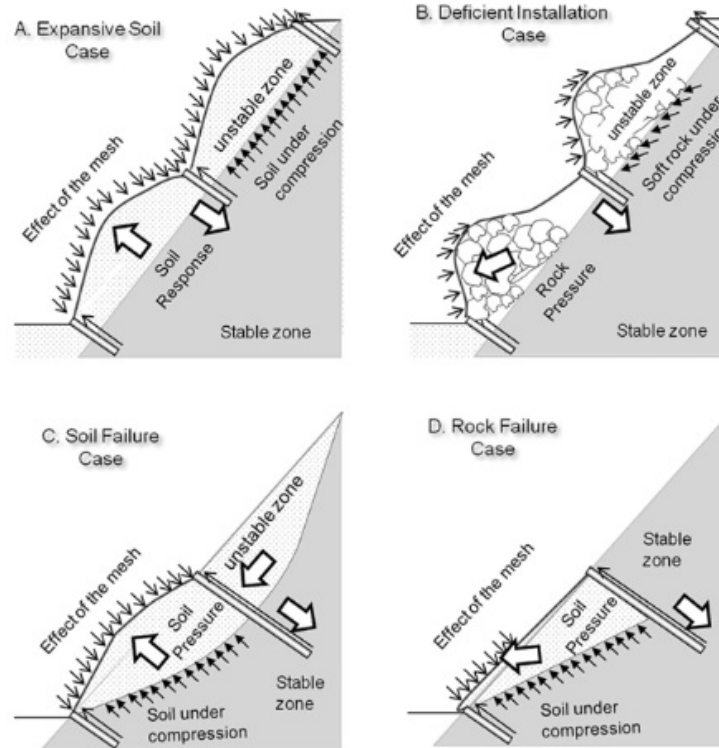


Fig. 2 Illustration of the variety in loading conditions on flexible facing systems according to [Castro-Fresno et al \(2009\)](#).

The aim of this article is to provide readers with a critical overview of knowledge and practice in FFS design, and to identify key research issues for improving this design. It is structured as follows. Firstly, the analytical models that have been proposed for the design of FFS are summarised in Section 2, describing their main characteristics. Secondly, the research work carried out to date is presented (Section 3). It is divided into two categories: experiments and numerical modelling. This section provides a general overview without going into a detailed description of their respective results and conclusions.

On this basis, Section 4 addresses the mechanical response of FFS with a view to highlighting the mechanisms governing this response and the influence of the various

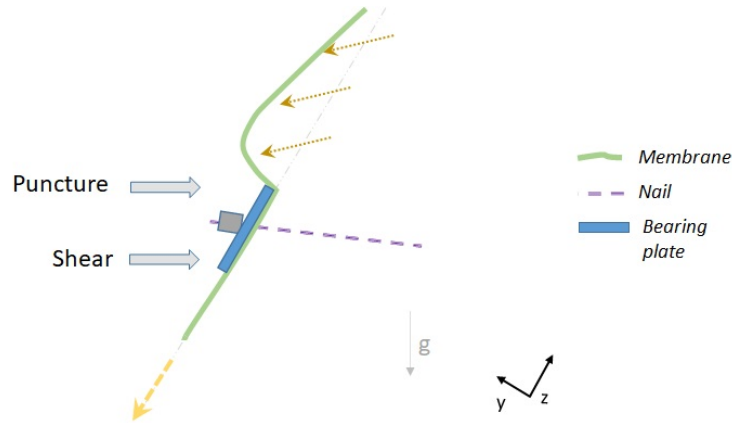


Fig. 3 In the nail vicinity, the membrane may fail due to a puncturing mechanism or to a shear mechanism.

parameters. This description allows us to discuss various aspects of FFS design. First, the discussion in Section 5 focuses on the use of experimental data and simulation results to study FFS response and design. The limitations of the available analytical methods are then discussed in Section 6.1, before presenting recently proposed design approaches (Sec. 6.2). Finally, a perspective consisting of improving the design criterion is discussed in Section 7.

2 Overview of existing design methods

Various methods have been proposed over the last two decades for selecting or designing FFS (Table 1). These methods are based on analytical models addressing the ground stability for estimating the load experienced by the FFS during its normal operation. Blanco-Fernandez et al (2011) provided a detailed description, comprehensive picture and critical review of most of these models.

These analytical models share the same general features, which are: (i) problem treated in 2 dimensions, (ii) stability issue addressed based on a Limit Equilibrium (LE) approach, while considering a Mohr-Coulomb failure criterion, (iii) failure occurs as translational sliding considering a plane surface, which is most often the base of

the unstable ground layer, (iv) the unstable ground volume has a uniform thickness, except at its extremities when slope of finite length are considered, and (v) the layer is discretized in rigid volumes, or blocks, as exemplified in Fig. 4.

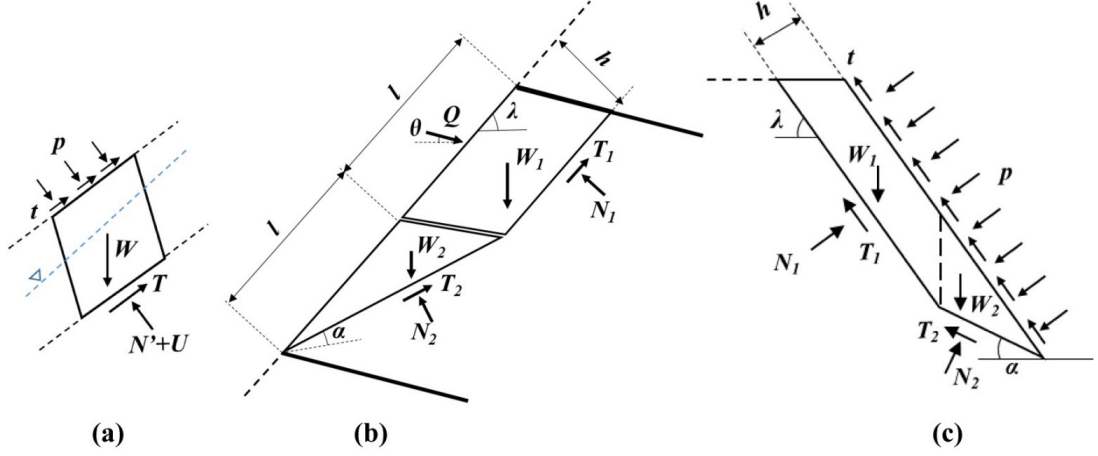


Fig. 4 Ground layer discretisation and forces considered in Limit Equilibrium approaches, for model 1 (a), model 6 (b) and model 3 (c). Illustrations from Pol et al (2020) where notations are defined.

Beyond these common features, differences exist between available analytical models. First, approaches either concern infinite slope failure or wedge failure mechanisms (see Fig 4). Second, the unstable ground volume is divided into a different number of blocks, generally from 1 to 5, the geometry of which differ from one model to another. Also, the considered instability is either global or local, this latter being located between nails. The length of the ground surface exposed to the stabilising effect by the membrane also differs from one method to the other (for example, some approaches consider that the membrane acts on the lower block only).

In addition, Models 1 to 7 consider FFS as active systems and neglect the elongation of the membrane. By contrast, models 8 and 9 were developed to be combined with a displacement-controlled FFS loading approach (Galli et al, 2020). In other

Table 1 Analytical models proposed in the literature for designing FFS

#	Source	Main features
1	Da Costa and Sagaseta (2010)	Infinite-length layer instability.
2	Da Costa and Sagaseta (2010)	Finite-length layer instability. Discretized in several wedges.
3	IberoTalud and Universidad de Cantabria (2005)	Finite-length layer instability. Discretized in two wedges. Membrane acts on both.
4	Ruegger and Flum (2000) ; Cala et al (2020)	Local instability, between two nail rows. Modeled as a single sliding block.
5	Ruegger and Flum (2000) ; Cala et al (2020)	Local instability, between two nails rows. Discretized in two blocks. Membrane acts on the lower one only.
6	Castro-Fresno (2000)	Similar to model # 5, with different blocks geometries.
7	British standard institution (2011)	Similar to model # 5, with different blocks geometries. Membrane acts on the two blocks.
8	Maccaferri (2021a,b)	Finite-length layer instability. For steep slopes. Discretized in 2-blocks. The membrane acts on the lower one only. Accounts for the stabilisation by the nail.
9	Maccaferri (2021a,b)	Similar to model # 8 but adapted to gentle slopes by considering a different lower block geometry.

words, the progressive increase in FFS loading with the displacement of the unstable volume is accounted for. This recent development will be discussed in section 6.2.

These analytical models rest on simplifications of the considered problem, consequently implying assumptions which acceptability and consequences have rarely been addressed in detail, at the exception of [Blanco-Fernandez et al \(2011\)](#). The simplifications in these analytical models will be discussed in section 6.

3 Available research literature

There is a wealth of literature dealing with the efficiency of FFS in stabilising ground layers on slopes. In view of improving their design, research works addressed the mechanical response of all or part of FFS based on experiments and numerical modelling. These research works are introduced in the following and their outcomes will be presented and merged when discussing the response of FFS, in section 4.

3.1 Experiments

The mechanical response of FFS and of their components may be characterised according to specific testing procedures which are briefly introduced in this section.

The determination of the mechanical characteristics of membranes considered square or rectangular membrane panels subjected to in-plane or out-of-plane loading.

In-plane loading (tensile test) consists in pulling one side of a rectangular or square panel while the panel sides parallel to the loading direction are either constrained (i. e. with no lateral contraction allowed) or free to move (UNI, 2012). EOTA (2016) specifies that rhomboidal mesh membranes should be loaded along the mesh longitudinal direction. In addition to some data provided by manufacturers, the literature provides results from tensile tests concerning hexagonal wire meshes (Bertrand et al, 2008), cable nets (Jimenez Fernandez et al, 2021) and rhomboidal mesh membranes (Von Boetticher and Volkwein, 2019). Comparison tests considering various membrane types are available in the literature (Muhunthan et al, 2005; Sasiharan et al, 2006; Berthet-Rambaud and Guillemin, 2006; Jimenez Fernandez et al, 2021).

Out-of-plane load tests consist in punch tests where a membrane panel secured at its boundaries is exposed to a load normal to its plane (Fig. 5). This loading is either concentrated or distributed over the membrane panel surface. In both cases, the loading is axi-symmetric with respect to the panel centre. Such tests aim at characterising

the membrane under loading conditions closer to that in the field. Concentrated loading (Fig. 5, left) may be assimilated to the case of the stabilisation of a rock block while the distributed loading test (Fig. 5, right) may be assimilated to the case of the stabilisation of ground layers. For both test types, tests presented in the literature were performed on square or rectangular membrane panels, of variable size. [Castro-Fresno et al \(2009\)](#) gave details concerning the way to conduct punch tests on net panels, either with concentrated or distributed loading.



Fig. 5 Concentrated and distributed load punch tests on a cable net. Pictures from [Castro-Fresno et al \(2008\)](#).

The concentrated load punch test is conducted using a punching element of a given dimension, which is a fraction of the panel size. The punching element is most often cylinder-like and its end is either planar, hemispherical or conical. The UNI standard ([UNI, 2012](#)) describes a protocol for such a test. Concentrated loading punch tests have been conducted on hexagonal wire meshes ([Gabrieli et al, 2019](#); [Pol and Gabrieli, 2021](#); [Pol et al, 2021b](#)), cable nets ([Castro-Fresno et al, 2008](#); [Trad and Limam, 2021](#)) and rhomboidal mesh membranes ([Morton et al, 2007](#)).

As for the distributed load punch test, common practice consists in covering the whole membrane surface with piled-up bags containing granular materials. Less data

are provided by the literature concerning this type of test compared to the concentrated load punch test. Punch tests with a distributed loading have been conducted on cable nets (Jimenez Fernandez et al, 2021; Castro-Fresno et al, 2009; Castro-Fresno et al, 2008) and rhomboidal mesh membranes (Justo et al, 2014). To the authors knowledge, there is no available data concerning hexagonal wire mesh membranes.

Fig. 6 illustrates the response of a membrane during distributed loading punch test. This figure evidences that the force opposed by the membrane to an out-of-plane loading slowly increases below a relative deflection displacement of 10%, corresponding to a 20% relative loading (Justo et al, 2014). This curve shape is observed for both distributed and concentrated out-of-plane loading and for all membrane types, i.e. with a rhomboidal mesh (Justo et al, 2014), a water-drop mesh (Trad and Limam, 2021), an hexagonal mesh (Gabrieli et al, 2019) and square mesh cable nets (Jimenez Fernandez et al, 2021).

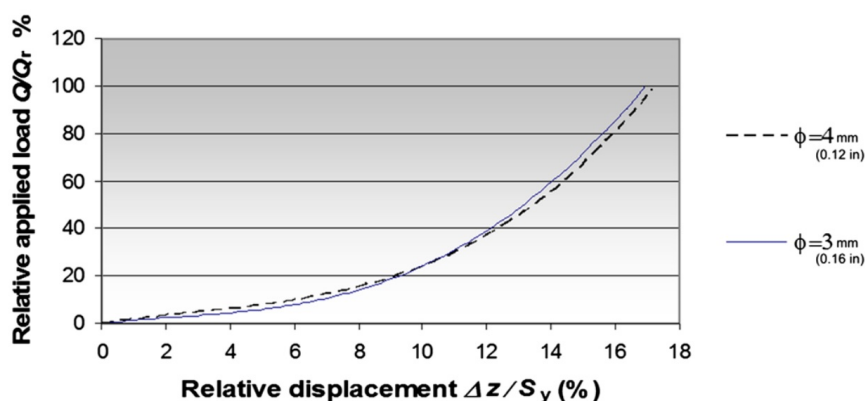


Fig. 6 Typical membrane punch test response. Illustration for a distributed loading and a rhomboidal mesh membrane, considering two wire diameters. Load relative to rupture load vs deflection relative to cord length. Figure from Justo et al (2014).

In addition, two specific tests are prescribed by EOTA (2016) for characterising the interaction between the nail plate and the membrane, in line with the failure mechanisms illustrated in Fig. 3. The first consists in a punch test where a nail plate

is pressed onto a membrane panel covering a ground layer (see Fig. 7). The second consists in pulling a membrane panel placed on top of a ground layer, in a direction parallel to the ground surface. The membrane panel is secured at its centre with a nail and a nail plate. Both tests are conducted until membrane failure. These tests are prescribed for rhomboidal mesh membranes by EOTA (2016).

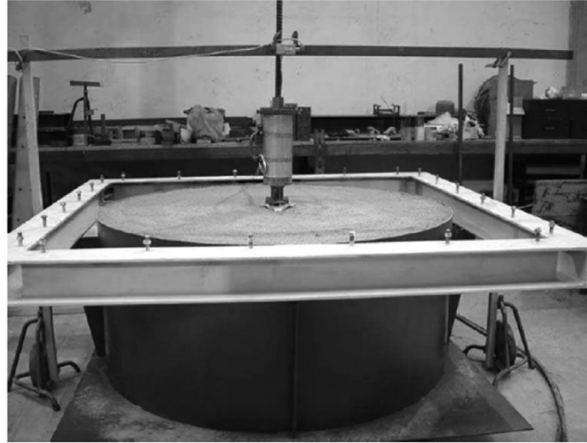


Fig. 7 Testing device for pressing a plate onto a membrane covering a soil layer. Picture from di Prisco et al (2010).

Tests where nail plates are pressed onto a membrane covering a ground layer allow quantifying the interaction between the membrane and the ground, in addition to that from the plate (di Prisco et al, 2010). Such tests were first conducted more than two decades ago (Ruegger and Flum, 2000). Nevertheless, the literature provides very limited data in relation to these test conditions.

The whole FFS may be tested in close-to-reality conditions as illustrated in Fig. 8 (Cala et al, 2013; Baraniak et al, 2014; Bucher et al, 2016; EOTA, 2016; Fonseca and Dias Trillos, 2020). Such experiments involve a large FFS, typically 12 * 10 m in dimensions, covering a ground layer with a 1.2m minimum thickness. The ground is contained in a steel frame, to which the FFS boundaries are attached via ropes. The

FFS also includes nails and nail plates regularly spaced. The ground layer has a uniform initial thickness and consists of dry and cohesion-less ground materials (sandy gravel and rounded gravel). The membrane is placed in active conditions by creating a trough around the nails. The test consists in progressively tilting the steel frame until soil failure occurs. The main results obtained from such tests and describing the strength of a given FFS is the inclination leading to failure. In addition, measurements include tension in the boundary ropes, securing the FFS to the steel frame, and force and displacement of the nails (EOTA, 2016). These tests offer the possibility of investigating the influence of some parameters related to the FFS or to the ground. Cala et al (2013); Bucher et al (2016); Fonseca and Dias Trillos (2020) provide some data collected during such tests.

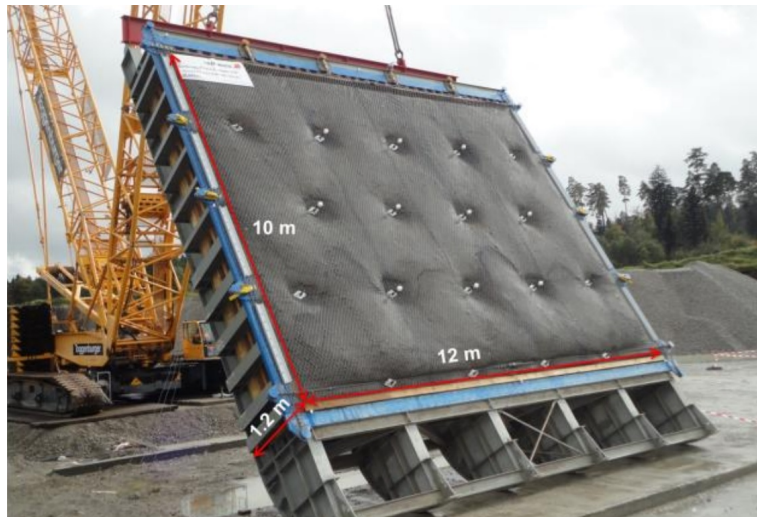


Fig. 8 Frame containing a soil layer stabilised by a FFS and which inclination is increased up to failure. Picture from Bucher et al (2016)

3.2 Numerical modelling

Since the very first numerical model of a FFS was proposed in the mid 2000's (Sasihran et al, 2006), numerical modelling has been widely used for addressing the response

of membranes and of small scale set-ups representative of FFS. Various modelling approaches and tools were used for modelling membranes made from cables (Sasiharan et al, 2006), rhomboidal mesh with high tensile strength (Morton et al, 2007; Castro-Fresno et al, 2008; del Coz Díaz et al, 2009; Xu and Tannant, 2016; Von Boetticher and Volkwein, 2019; Xu et al, 2019) and from hexagonal wire meshes (Sasiharan et al, 2006; Pol et al, 2018; Gabrieli et al, 2018, 2019; Gabrieli and Pol, 2019; Pol et al, 2020; Pol and Gabrieli, 2021; Pol et al, 2021a,b; Karampinos and Hadjigeorgiou, 2021). At the exception of Blanco-Fernandez et al (2016), most developments concern 3D models.

The finite element method -FEM- was considered by various authors, using different codes. *ABAQUS* was used by Sasiharan et al (2006) and by Boschi et al (2020, 2021), *FARO* by Morton et al (2007), *ANSYS* by Castro-Fresno et al (2008), del Coz Díaz et al (2009) and Blanco-Fernandez et al (2016) and *PLAXIS 3D* was used by Lehn and Biczók (2020) and Lehn et al (2021). di Prisco et al (2010) used an house-made code. Membranes were modelled with FEM as continuous membranes, considering an elastic (Muhunthan et al, 2005; Sasiharan et al, 2006; Blanco-Fernandez et al, 2016; Lehn and Biczók, 2020; Boschi et al, 2021; Lehn et al, 2021; Jimenez Fernandez et al, 2021) or an elastic-perfectly plastic behaviour (Blanco-Fernandez et al, 2016; Boschi et al, 2020). Some authors considered a Von-Mises membrane failure criterion (Jimenez Fernandez et al, 2021; Boschi et al, 2020). One will note that membrane anisotropy was rarely accounted for in these models (Boschi et al, 2020; Lehn and Biczók, 2020; Lehn et al, 2021). The membrane modulus was derived from tensile tests (Sasiharan et al, 2006) or by calibration against concentrated load punch tests data (Jimenez Fernandez et al, 2021). FEM was also used by few authors for modelling the exact geometry of the mesh and accounting for plasticity, thus allowing accounting for both geometrical and material non-linearities (Castro-Fresno et al, 2008; del Coz Díaz et al, 2009; di Prisco et al, 2010).

The discrete element method -DEM- was used for conducting numerous research works considering membranes with either an hexagonal (Pol et al, 2018; Gabrieli et al, 2017, 2018, 2019; Gabrieli and Pol, 2019; Pol et al, 2020; Pol and Gabrieli, 2021; Pol et al, 2021a,b; Pol and Gabrieli, 2022) or a rhomboidal mesh (Xu and Tannant, 2016; Von Boetticher and Volkwein, 2019; Xu et al, 2019, 2020). In the DEM framework, each mesh may be modelled as a collection of particles or as a collection of cylinders forming the segments (Gabrieli et al, 2017). The particles are generally located at the mesh nodes (Thoeni et al, 2013; Bourrier et al, 2015; Pol et al, 2018). An alternative consists in locating the particles at the mesh centre, in a "cell-based" approach where remote interactions between particles are calibrated considering the overall mechanical response of the membrane panel (Nicot et al, 2001; Dugelas et al, 2019). The very frequent use of the DEM in this context is due to its advantages in comparison to continuum modelling in particular. These advantages are the possibility to model accurately all components of the system in a same environment (membrane, ropes, soil), the ease of modelling the large displacements and deformation experienced by these components, the ease in accounting for mechanical and geometrical non-linearities (and thus, anisotropy)(Coulibaly et al, 2017), the possibility to efficiently handle failure (e.g. wire breakage) and multiple contact problems. The open source code YADE-DEM (Angelidakis et al, 2024) was chosen by several authors (e.g. Thoeni et al (2013); Dugelas et al (2019); Pol et al (2021a)), in particular because it includes models of hexagonal wire mesh and beams developed by Bertrand et al (2008) and by Bourrier et al (2013) respectively. Alternatively, Von Boetticher and Volkwein (2019) used a house-made DEM model and the DEM code 3DEC (Itasca consulting group Inc, 2014).

These various FEM and DEM membrane models allowed addressing the response of membrane panels to in-plane tensile loading (e.g. del Coz Díaz et al (2009); Von Boetticher and Volkwein (2019)) and to out-of-plane loading, with concentrated

Castro-Fresno et al (2008); Pol et al (2021b); Gabrieli et al (2018) or distributed loads Castro-Fresno et al (2008); Gabrieli et al (2018). These models also served for addressing the response of membrane panels or FFS to punctual loading when varying the nailing spacing or panel size, nailing pattern, location and size of the punching element and nail plate size (Xu et al, 2019; Pol et al, 2021a,b).

In the continuation of the development of these membrane models, some researchers have addressed the response of systems combining ground and membrane. The response to punch loading of a membrane covering a ground layer was modelled in particular for evaluating the respective contribution of the membrane and the soil, while accounting for the influence of many parameters such as the nail plate size and the membrane and soil mechanical characteristics (di Prisco et al, 2010; Gabrieli and Pol, 2019; Boschi et al, 2020, 2021; Pol and Gabrieli, 2022). The FEM model developed by Boschi et al (2020, 2021) considered the soil as elastic perfectly plastic. Gabrieli and Pol (2019); Pol et al (2020) modelled both the membrane and the soil with DEM, considering the former as a frictional granular material made of spheres. Large-scale FFS were modelled with DEM by Pol et al (2018, 2020). Blanco-Fernandez et al (2016) proposed an approach consisting in coupling SPH (Smoothed-particle hydrodynamics) for modelling the ground, to FEM for modelling the membrane. The problem was addressed in 2D and the unstable slope surface was detected using a Bishop limit equilibrium approach. The ground was modelled as an elastoplastic frictional material without cohesion. This model was later extended to 3D. Lehn and Biczók (2020) and Lehn et al (2021) studied large-scale FFS, modelled using FEM, to address the effect of ground cohesion. Some of these simulation results were compared with large-scale tests results (Jimenez Fernandez et al, 2021; Lehn et al, 2021).

These numerous models have been used for addressing various issues related to the response of various types of membranes and FFS. Nevertheless, model validation

against close-to-reality testing conditions of large FFS is still rare due to limited available experimental data sets.

4 Mechanical response of flexible facing systems

The knowledge gained through these numerous research works allows describing the complex response of FFS when used to stabilise ground layers on slopes. In particular, experimental and numerical inputs highlight some peculiar mechanisms involved in the membrane response, in terms of both the system deformation and the load transfer through the various components of the FFS.

For a given situation in terms of ground volume and mechanical characteristics to stabilise, the FFS characteristics with influence on the ability of the membrane to develop the required confining stress with a limited deflection are in particular the tensile load response of the membrane, the pretension in the membrane, the addition of reinforcement ropes, the nail spacing and pattern and the mesh shape.

It is worth highlighting that the influence of one of these parameters on the mechanical response of a given FFS depends on the value of some other parameters. For example, it will be seen that the influence of the nail spacing depends on the nailing pattern, and the influence of this latter depends on the mesh shape. All these interactions makes the behaviour of FFS very complex.

In the following, the influence of the governing parameters will be discussed for highlighting this complexity, based on findings from research referred to in section 3

4.1 Boundary conditions

In the field, nails delineate membrane panels experiencing large displacements and strains. The displacements at the boundaries of these panels may be limited in particular by ropes running from one nail to another.

The influence of conditions at the panel boundaries on the membrane response to an out-of-plane loading was evidenced by Bertolo et al (2009) comparing in situ testing and lab testing on cable nets and hexagonal wire mesh nets. In the field, the nailing pattern was square with a 3m nail spacing. Similarly, the net panel subjected to punch test in the lab was 3m*3m in dimensions and had fixed boundaries. The panel centre displacement required for reaching a 10 kN load ranged from 300 to 1000 mm in the field compared to 200 mm in the lab.

Pol et al (2021b) demonstrated that the displacement required for reaching a given reaction force by the membrane was much less when the loading was uniformly distributed on the whole FFS compared to the case of a concentrated loading ('Test A' vs. 'Test B' in Fig. 9). This is due to the fact that, the symmetry in loading with respect to the panel boundaries which is observed in the former case causes the displacement at the panel boundaries to occur in the direction perpendicular to the membrane plane only (y-axis in Fig. 1). By contrast, displacement occurs in 3 directions in the latter case ('Test A'). In other words, the displacement at the panel boundaries depends on the loading beyond the boundaries, with an influence on the force-displacement response at the centre of the loaded panel, and thus on the local confinement capacity of the membrane.

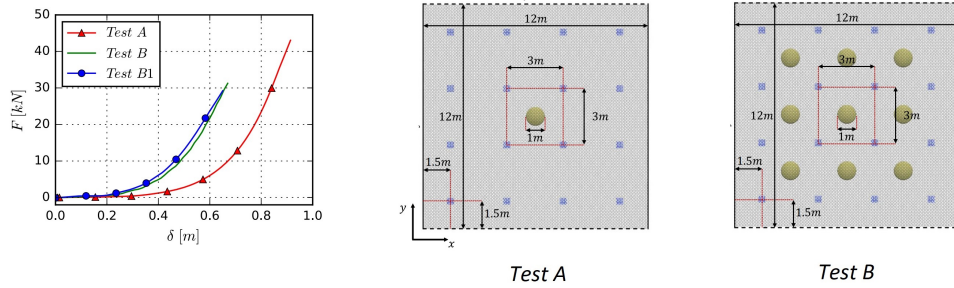


Fig. 9 Response of a FFS against a concentrated loading in the centre of the central panel only ('Test A') and in combination with concentrated loading in the centre of all panels ('Test B'). 'Test B1' is not discussed here. Case of an hexagonal wire mesh. From Pol et al (2021b) where notations are defined.

These observations demonstrate that the membrane confinement capacity at a given point increases with the displacement constraints at the boundaries of the panel. In the field, the displacement at the panel boundaries relates to loading uniformity, which results in loading symmetry with respect to the panel boundaries. This condition is not always satisfied. The displacement at the panel boundaries can also be restricted thanks to reinforcement ropes running from one nail to another. This latter case results in a lower panel boundary displacement in the y-axis direction (see Fig. 1).

4.2 Nail spacing

Punch tests in the lab are performed on membrane panels typically 3m*3m in size, which is considered representative of the size of membrane panels delineated by nails in the field. Nevertheless, the nail spacing on-site may be different, with consequences on the effective membrane response, in particular in terms of force it opposes to an out-of-plane displacement.

This was addressed by [Castro-Fresno et al \(2008\)](#) simulating the response to concentrated punch tests of cable net panels increasing their size. The displacement induced by a given load was shown to increase linearly with the distance from the panel centre to its corner

The dependence of the force-displacement system response on the nail spacing or, by extension, to the area comprised between nails is observed in Fig. 10 showing that the confinement force by the membrane when a 0.3 m displacement is reached drastically decreases with this area, for both a rectangular or a rhomboidal nail pattern. A similar trend was observed with membranes with an hexagonal mesh pinned following a rectangular pattern ([Pol et al, 2021b](#); [Marchelli et al, 2023](#)). These authors clearly demonstrated that the increase in force with the displacement is higher when the nail spacing decreases.

In conditions closer to that in the field and considering a ground layer (Fig. 8), the experimental results presented by Bucher et al (2016) lead to the conclusion that, in some configurations, increasing the nail spacing from 3.0 to 3.5m results in a decrease of the failure inclination exceeding 10%.

In addition, the spacing has a significant influence on the load at the nails. Simulations by Sasiharan et al (2006) led to the conclusion that the load on the nail is linearly proportional to the nail spacing, in a ratio of 1:1 approximately when considering different membrane types and ground layer roughness.

4.3 Nail pattern

The results presented in Fig. 10 also reveal that a rectangular nail pattern (pattern A) provides highest confinement forces than a rhomboidal one (pattern B) for a membrane with a rhomboidal mesh. More precisely, highest values are obtained for rectangular patterns where the ratio between the distance between nails along horizontal (H) and that along the vertical (V) is in accordance with the aspect ratio of the mesh opening. These cases are shown with empty symbols in this figure.

In line with this observation, simulation results presented in Fig. 11 reveal that the response to concentrated load of a pinned membrane with a rhomboidal mesh depends on the arrangement of the nails with respect to the mesh shape. A nailing pattern geometry in accordance with the mesh opening aspect ratio (1.75 in this case) leads to a direct load transfer to the nails, with a mobilised force of 4.25 kN for a 0.3 m displacement (Fig. a vs b, resp.). By contrast, this value drops to 1.74 kN in case the nailing pattern is not in accordance with the mesh opening aspect ratio (right figure). This is even more noticeable that the distance to the nearest nail is smaller in the second case than in the first one. In other words, the second configuration is less efficient in developing high stabilising force while having a higher nail density. This is

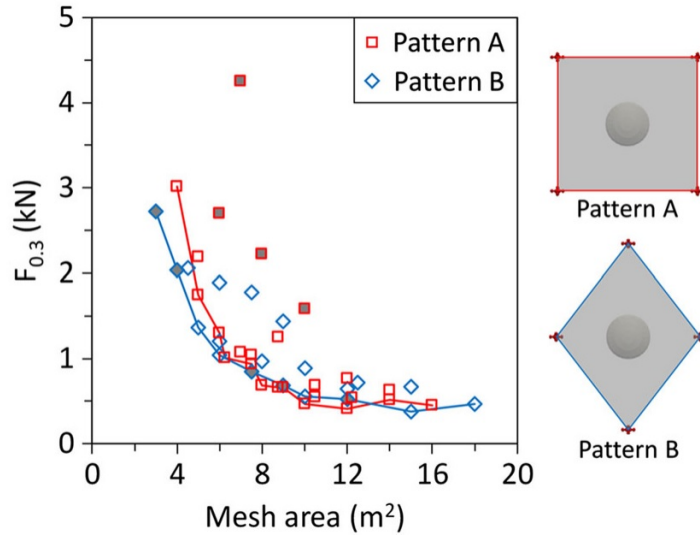


Fig. 10 Influence of the panel size and nailing pattern on the membrane retaining force for a 0.3 m deflection. Simulation results concerning a membrane with a rhomboidal mesh from [Xu et al \(2019\)](#).

because, in this case, the load is not transferred to the nearest nails but to nails at a longer distance.

A deeper investigation of the punch test response of a membrane with a square mesh clearly shows the difference in load transfer from the loaded area to the nails (Fig. 12 a, b). For such a mesh, a rhomboidal nailing pattern results in the direct load transfer to the nails. In addition, and as a corollary, the deflection required for reaching a similar force value (37kN approx.) is much higher when the nailing pattern is square (approx. 364 vs. 135 mm).

By contrast, results from [Marchelli et al \(2023\)](#), which concern membranes with an hexagonal mesh pinned following a rectangular pattern, revealed a very limited influence of the horizontal-to-vertical distance between nails on the force vs deflection response of the membrane.

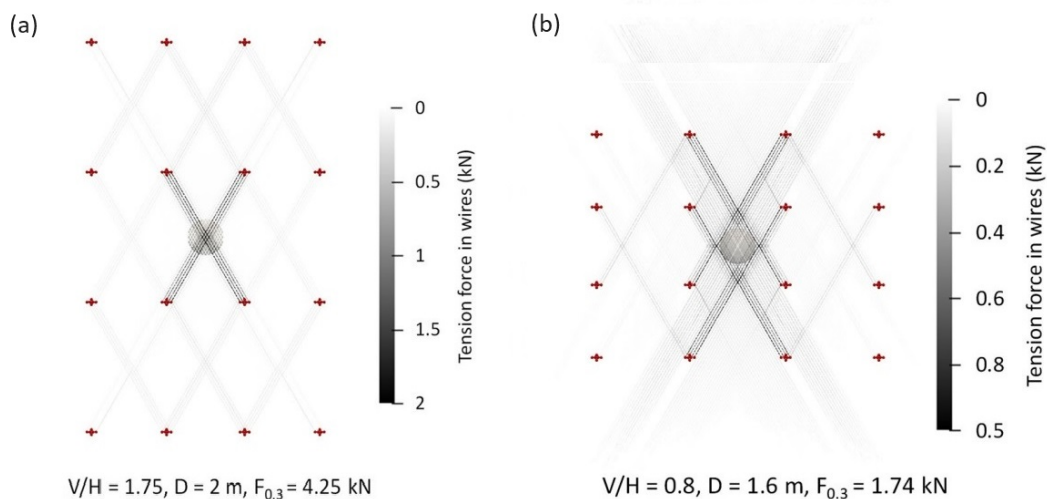


Fig. 11 Force transfer within a membrane with a rhomboidal mesh when exposed to localised normal loading. Influence of the V/H ratio, where V and H are the distances between nails along the vertical and horizontal axis respectively. D is the distance of the punch device centre to the nearest nail. $F_{0.3}$ is the reaction force for a 0.3 m punch device displacement. Adapted from [Xu et al \(2019\)](#).

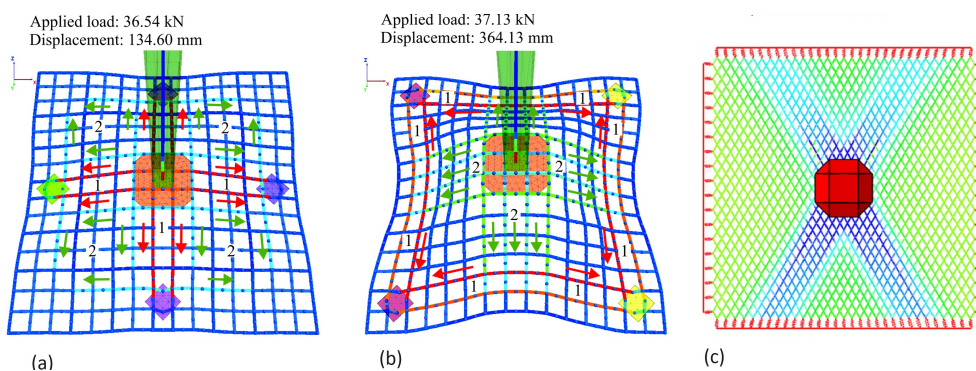


Fig. 12 Load transfer within membranes from the loaded area : to the nails for a membrane with a square mesh and two different nailing patterns (a, b) and, to the panel boundaries via aligned wire segments in case of a rhomboidal mesh (c). From [Karampinos and Hadjigeorgiou \(2021\)](#) and [Hambleton et al \(2013\)](#) resp.

4.4 Mesh shape

The previous section has suggested that the mesh shape plays a role in the load transfer from the loaded area to the panel boundaries or nails, with a possible influence on the membrane deformation under a given loading. This was evidenced long ago based on

lab experiments and is exemplified in Figs. 12a, b. Most of the load induced by an out-of-plane loading on the membrane is conveyed to the membrane panel boundaries and nails, if any, through aligned wire segments, similar to what is described from tensile test experiments in [Von Boetticher and Volkwein \(2019\)](#) in the case of a membrane with a rhomboidal mesh. Aligned segments offer the most stiffer paths and, for this reason, loads concentrate along these paths. Other paths from the loaded area to the panel boundaries consist of a succession of segments that can bend one with respect to the other and are consequently less stiffer. This bending is associated with mesh distortion, which depends on the mesh initial geometry ([Lambert et al, 2011, 2023](#)). The directional nature of load transfer within the membrane was observed with rhomboidal meshes (Fig. 12, c), cable nets as well as with water-drop meshes ([Trad and Limam, 2021](#)) and hexagonal meshes ([Thoeni et al, 2013](#)). Nevertheless, in these two latter cases, the mesh shape and its distortion may result in a more complex load distribution pattern where the load transfer direction may not exactly follow the segments direction.

The directional nature of load transfer was shown to have an influence on the membrane deformation under close to reality conditions, and consequently on its confining effect. Indeed, it can be seen from Fig. 13 that the membrane displacement between two nails belonging to two horizontal adjoining rows is restricted. This is because, in this case where the nailing pattern corresponds to the mesh geometry, the wire segments forming the meshes are aligned between the two nails. The succession of aligned segments acts as a single segment, which stiffness is high, restraining membrane strain between these nails, thus restricting membrane displacement. As a consequence, the ground below this line is exposed to a higher confining effect. To some extent, this effect leads to the delineation of an unstable ground volume between nails, as illustrated in Fig. 13.

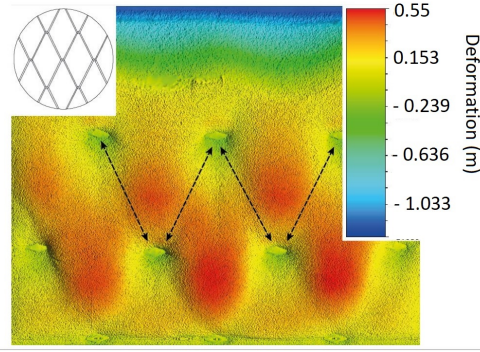


Fig. 13 Deformation of a FFS during the test illustrated in Fig. 8. The arrows evidence the restriction in membrane displacement between nails, which is associated with the mesh shape. Adapted From [Bucher et al \(2016\)](#).

4.5 Nail plate

The primary function of a nail plate is to transfer load from the membrane to the nail, which diameter is small compared to the membrane mesh openings ([British standard institution, 2011](#)).

In case the nail is in active condition, the nail plate directly applies on the ground layer a confining load as illustrated in Fig. 14. This confining effect, which is also revealed on Fig. 13, directly contributes to the ground layer stability by reducing the length and width of the ground volume that is prone to sliding (i.e. a_d in Fig. 14) ([Cala et al, 2020](#)). A similar confining effect is observed for passive FFS, from the moment ground movement initiates. This local effect motivated the development of analytical models considering local instabilities, that is to say concerning ground volumes between nails (models #4 to 7 in Table 1).

The literature suggests that the nail plate dimensions have an influence on both the confining pressure applied on the ground and the membrane failure occurrence. [Bucher et al \(2016\)](#) observed that larger nail plates result in significantly higher lateral stabilising effect by the plate. This increase in confining force was also evidenced by other authors, considering the loading case illustrated in Fig. 7 ([Gabrieli and Pol, 2019](#); [Boschi et al, 2021](#); [Pol and Gabrieli, 2022](#)). Nevertheless, the derived benefit tends to

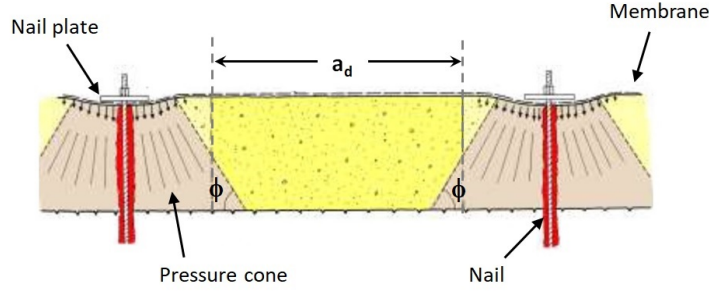


Fig. 14 Cross-section of the ground layer along the horizontal axis showing the lateral expansion of the confining stress due the nail plates. In this figure ϕ is the soil friction angle and a_d is the length of the unstable soil volume between nails (adapted from [Cala et al \(2020\)](#)).

diminish with the plate size, as suggested by [Pol and Gabrieli \(2022\)](#). Considering a FFS exposed to localised loading, [Pol et al \(2021b\)](#) also showed that increasing the nail plate dimension improves the punch resistance, or mesh-plate connection resistance. This effect was explained by the higher number of wires intercepted by the nail plate. The same observation was made by [Marchelli and Giacchetti \(2021\)](#). It is thought that this effect is also relevant for the case of a membrane experiencing distributed loading.

It can be noticed that the influence of the nail plate dimensions on the system response also accounts for the confinement effect by the membrane, and thus on the characteristics of the membrane. For example, based on tests with the facility presented in [Fig. 8](#) and considering a layer of rounded gravel, [Bucher et al \(2016\)](#) observed that the confining effect around the plate is even more pronounced when the membrane has a high puncturing resistance, with an increase of the failure inclination from approximately 56° to 83° when the membrane puncture resistance increases from 40 to 140 kN.

4.6 Reinforcement ropes

Reinforcement ropes taut between nails aim at reducing the membrane deflection, thus increasing the confining pressure applied by the membrane on the unstable layer, and in particular below the ropes.

For example, [Pol et al \(2020\)](#) considered diagonal reinforcement ropes superimposed on a membrane with an hexagonal mesh and showed that the force applied by the FFS on the ground layer for a given membrane deflection was doubled with respect to that of the membrane alone.

[Marchelli and Giacchetti \(2021\)](#) explained that the presence of reinforcement ropes changes the conditions at the panel boundaries reducing the panel deflection for a same pressure. Reinforcement ropes also favour stress distribution in the membrane, and thus prevent from stress concentration in the nail plates vicinity where failure mechanisms described in [Fig. 3](#) occur. These authors demonstrate that a rhomboidal rope layout is an optimum on a design point of view, in terms of cost reduction.

5 On the use of tests and modelling for addressing the response of FFS

Research findings presented in the previous section bring to light some vigilance points as for current practices in terms of experiments and numerical modelling used for addressing the mechanical response of FFS or for designing FFS. These vigilance points constitute some possible improvement tracks and research issues.

5.1 Experimental characterisation of membranes and FFS

5.1.1 Lab tests

Membranes used in FFS are generally characterised based on punch tests, either applying concentrated or distributed loading. For membranes with a rhomboidal mesh, [EOTA \(2016\)](#) requests the former as well as the punch test on a membrane supported by a ground layer ([Fig. 7](#)). Considering that these latter punch tests are representative of field conditions and that the obtained data may be used for design purpose raises questions.

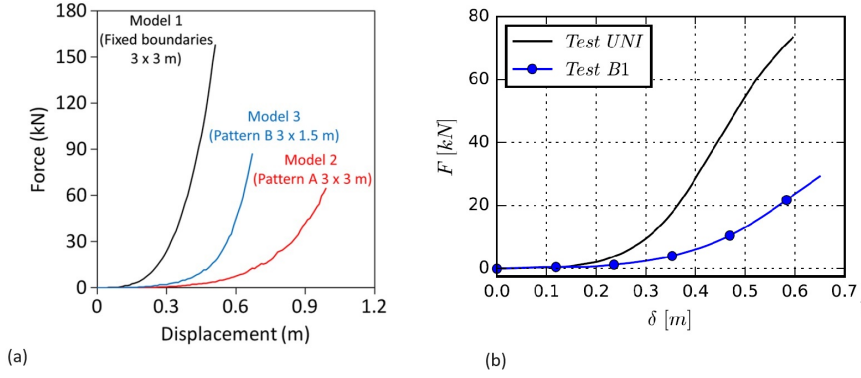


Fig. 15 Influence of the membrane panel boundary conditions on its response to localised out-of-plane loading. Comparison between lab tests boundary conditions (i.e. 'Model 1' in fig. (a) and 'Test UNI' in fig. (b)) and conditions closer to that in the field. Results from [Xu et al \(2019\)](#) for a membrane with a rhomboidal mesh (a) and from [Pol et al \(2021b\)](#) for an hexagonal mesh (b).

The first main one relates to the panel boundary conditions. Results presented in [Fig. 15](#) demonstrate that punch tests conducted in the lab result in a reaction force at least twice higher than when considering boundary conditions in better agreement with the field. Analogously, [Xu et al \(2019\)](#) showed that lab test conditions result in a much smaller deformation for reaching a given confining effect than in the field. This difference in response is due to the fact that displacements at the panel boundaries are much more restricted during lab tests than in the field, which results in an overestimation of the confining capacity offered by the membranes when derived from these standardised tests. This overestimation is significant and clearly constitutes the most critical point if not accounted for in a design perspective.

The second main difference between punch test and field conditions concerns the loading exerted on the membrane. In the field, the loading is distributed over the whole panel delineated by the surrounding nails while punch tests consider a concentrated load which difference was shown to have a significant influence on the FFS response ([Castro-Fresno et al, 2008](#); [Castro-Fresno et al, 2009](#); [Gabrieli et al, 2018](#)). The experiments presented in [Castro-Fresno et al \(2008\)](#) as well as the simulations presented in [Gabrieli et al \(2018\)](#) showed that, for a given loading, the deflection is significantly

reduced when the load is distributed compared to the case where it is concentrated. Besides, the test conditions consider a symmetry in loading with respect to the panel centre while in the field the centre of pressure is shifted downward with respect to the panel centre (see Fig. 2) and the load is not normal to the membrane plane. This globally results in a significant difference between load transmitted to upper nails and that transmitted to lower nails. Loading inclination is thought to increase the influence of friction between the ground and the membrane, and secondary membrane if any, for both fine and coarse granular layers (Sasiharan et al, 2006; Castro-Fresno et al, 2008; Gratchev et al, 2015; Gabrieli et al, 2018; Pol et al, 2020; Jimenez Fernandez et al, 2021). The eccentricity of the loading with respect to the panel centre was also shown to have an influence on the panel force-displacement response (Pol et al, 2021b).

Globally, the difference in loading and boundary conditions between punch tests in the lab and the field has consequences on the load distribution in the membrane, and consequently on the load transferred to the other FFS components, namely the ropes, nail plates and nails. Gabrieli et al (2018) showed that the force transmitted to the nails increases much more with the deflection in case of a distributed loading than with a concentrated loading. Up to now, a limited number of research have addressed this issue while it is extremely intricate as it involves various mechanisms depending on many parameters. Tests conducted in the lab constitute conformance tests and the derived data are of great value for characterising panels. Because the test conditions are easy to account for in an accurate way in the simulations, these data are useful for calibrating numerical models of membranes. However, these lab tests are far from being performance tests due to the difference in conditions between the lab and the field. Overcoming this limit could rely on the approach proposed by Pol et al (2021a,b) and by Marchelli et al (2023) which consists in computing the confining effect by the membrane from the mechanical characteristics derived from a standardised punch test (UNI, 2012) while accounting for the site-specific conditions (nail spacing, loading

eccentricity...). It seems that this approach which was developed for an hexagonal mesh membrane used to stabilise rock blocks could be adapted to any membrane type when used for stabilising ground layers.

Punch tests where a plate is pressed onto a membrane covering a soil layer offer more realistic membrane loading conditions compared to punch tests as it induce membrane bending and tension at the plate vicinity which mechanisms lead to membrane failure (see Fig. 3). The only and moderate limitation with this test relates to the loading axi-symmetry with respect to the tested system, which contrasts with the real situation illustrated in Figs 2 and 3. In addition, the system response significantly depends on the ground modulus and cohesion, suggesting that test results on a given membrane and a given ground may not be extrapolated to other situations (di Prisco et al, 2010; Boschi et al, 2020; Pol and Gabrieli, 2022).

Last, and not necessarily least, all the tests concern panels of a given size, while in the field the nail spacing may differ.

5.1.2 Large-scale tests

Large-scale tests on FFS consisting in progressively inclining a steel frame containing a ground layer with uniform thickness (Fig. 8) were designed to offer close-to-reality conditions while being conducted in well controlled conditions. Nevertheless, some questions raise as for the realism of the test conditions by comparison with that in the field. The first one concerns the active condition which will be discussed in the following. The second one concerns the layer thickness uniformity and the last one relates to the progressive frame tilting. These points are in particular thought to have a significant influence on the mechanisms leading to ground layer instability and, consequently on the mechanisms with influence on the interaction between the ground layer and the membrane. A thorough investigation, for example based on numerical simulations could provide insights into the influence of these test conditions on the FFS mechanical response, in terms of load and deformation.

Besides, the ground characteristics may have a strong influence on the FFS efficiency. For example, a 10% failure inclination difference was observed between sandy gravel and rounded gravel (Bucher et al, 2016). Considering a similar configuration, simulations by Lehn and Biczók (2020) suggested that cohesion has a major influence on the FFS deformation and on the force within the membrane in the slope direction. More generally, the influence of the ground characteristics was evidenced by various authors (Justo et al, 2014; Gabrieli and Pol, 2019; Boschi et al, 2020; Pol and Gabrieli, 2022) which confirms that the extrapolation to other ground materials should be made with caution.

Last, the inclination at failure, which results from these tests, is not necessarily the most relevant data when the aim is to design an FFS for a specific slope inclination. Other measures made along the test are much more relevant in this purpose (e.g. force in the ropes and nails, membrane deflection...).

5.2 Numerical models

First of all, it is worth mentioning the substantial computational effort required, ranging from hours to days of simulations, for such complex simulations whatever the approach chosen, which is not explicitly mentioned in the concerned articles.

The different modelling approaches dedicated to simulate the response of FFS to concentrated or distributed static out-of-plane loading were all shown relevant and accurate in this context. The DEM naturally accounts for large displacements and for complex materials behaviours provided that classical cautious checks are performed (e.g. time convergence or energy balance). On the contrary, specific numerical implementations have to be chosen for a correct modelling when using FEM or Finite Difference (FD) models. In particular, algorithms able to integrate large displacements, elastoplastic materials, and potentially dynamics and contacts, have to be chosen.

Most of the models considering the membrane as a continuous body do not account for the membrane intrinsic geometrical and mechanical anisotropies, which are in particular related to the mesh shape and progressive distortion. Anisotropy has a dramatic influence on the membrane response. For example, in case of a membrane with a rhomboidal mesh, changing the tensile loading orientation results in a change in stiffness in a ratio of 1 to 8, a tensile strength reduction by a range of more than 2 (Justo et al, 2014; Von Boetticher and Volkwein, 2019) and an increase in failure strain by a ratio of 4 (Justo et al, 2014). Anisotropy also explains the preferential path for the load transfer in the membrane under out-of-plane loading (Fig. 11 and 12). In addition, a membrane modeled as a continuous body makes it difficult to account for some local effects such as interlocking between the membrane and debris or local mesh failures. It is thus not recommended to model membranes as continuous bodies, in particular if anisotropy and plasticity are not accounted for.

As regards to the explicit modelling of the interaction between the FFS and unstable ground volume, the SPH-DEM coupled approach employed by Blanco-Fernandez et al (2011) and by Jimenez Fernandez et al (2021) revealed efficient. One can notice two limitations to the general use of such coupling approaches:

- the capacity of SPH to model complex ground constitutive models. Indeed, Blanco-Fernandez et al (2011) and Jimenez Fernandez et al (2021) considered only frictional grounds.
- the need to use complex FEM models involving large displacements and elasto-plasticity for non-associated materials. Thorough analysis of the available software should thus be done prior to modelling.

The DEM approach was also successfully used in this context (Pol et al, 2018, 2020; Pol and Gabrieli, 2021). The main limitations with this approach for further investigations in this context are :

- the modelling of realistic grounds, in particular fine grounds.

- the computational duration for large 3D configurations.

Although it was not extensively used in this context, Finite Difference (FD) or FEM models for a complete modelling of the FFS interacting with unstable ground volumes could constitute a relevant option to be evaluated. The coupling between FEM and Material Point Methods (MPM) might also constitute a good option.

6 On available design approaches

6.1 Analytical approaches

As any model, analytical design approaches presented in Table 1 are based on simplifications and assumptions, which consequences on the model prediction correctness have been marginally evaluated up to now, at the exception of [Blanco-Fernandez et al \(2011, 2016\)](#). Available analytical models share some main features related to the fact that a 3D problem is treated in 2D, to the active behaviour assumption and the use of Limit Equilibrium approaches. Even though FFS have been successively designed for decades, discussing these features potentially raises some limitations and helps in identifying design method improvement tracks.

6.1.1 2D assumption

All analytical models address the design of FFS considering a cross section along the steepest slope (i.e. in the (y, z) plane in Fig. 1). As a consequence, the displacement and mechanisms occurring out of this plane are not accounted for, raising some comments.

The load transfer within membranes was shown to mainly concentrate along aligned wire segments, with an orientation that depends on the shape of the mesh and spatial distribution of the nails. In the case of a FFS which membrane mesh is rhomboidal, the direction of this preferential load transfer path is not aligned with the line of maximum gradient, as illustrated in Fig. 13. In such a situation, a 2D approach can't accurately account for load transfer to nails. For the same reason, the reinforcement

effect of ropes laid out following a rhomboidal pattern can not be correctly accounted for with a 2D approach. This was addressed by [Blanco-Fernandez et al \(2016\)](#) which findings suggest that 2D offers a less restrained situation when dealing with a FFS integrating reinforcement ropes that are not horizontal.

The limitations of 2D approaches also concern the ground layer. [Fig. 13](#) suggests that the unstable volume between nails, which depends on the nail pattern, can not be accounted for a correct way with a 2D model in the (z, y) plane (see [Fig. 1](#) for the axes). In addition, mechanisms leading to ground layer instability develop in 3 dimensions, in particular due to the presence of the nails and nail plates ([Pol et al, 2020](#)).

[Bucher et al \(2016\)](#) compared estimations based on model 4 (see [Table 1](#)) to experimental data obtained using the facility presented in [Fig. 8](#). The authors concluded that this model underestimates the inclination angle at failure, with a difference ranging from 16 to 25%. The difference increases with the nail spacing which trend is attributed to the 2D assumption. The authors also explicitly state that the moderate agreement between the computed value and the experimental one stems from the fact that the model doesn't account for the membrane/nail interaction, which limitation is also related to the 2D assumption.

It thus seems that there is convergence towards the conclusion that, even if convenient, 2D approaches do not allow accounting for the actual response of the FFS.

6.1.2 Active behaviour assumption

A design where the structure is active is considered preferable to avoid ground movements generating high tensile forces in the membrane, with detrimental effects on the membrane and/or the nails ([Castro-Fresno et al, 2009](#)). Active systems are well adapted and have been used for decades for stabilising single rock blocks. It requires prestressing the system (membrane, ropes, nails) in the aim of reaching a high confining stress from low membrane deflection. Meeting this requirement for the stabilisation

of ground layers implies creating trough around the nail plates (Bucher et al, 2016; Fonseca and Dias Trillos, 2020). Nevertheless, there are situations where achieving the active behaviour is hardly feasible. This is for example the case when dealing with concave surfaces or for some ground and slope characteristics. In addition, Blanco-Fernandez et al (2011) suggested that creating troughs allows tensioning the membrane in the nail plate vicinity and may have limited effect away from the nail plate.

Blanco-Fernandez et al (2011) stated that the hypothesis of an active behaviour had not been demonstrated (at least until 2011) and asserted as a main conclusion that FFS are not active. Later, Blanco-Fernandez et al (2013) provided evidences of passive behaviour based on field measurements on specific sites. These authors noted that the real tensile force in the ropes was very low compared to the ultimate strength and that the resulting confining pressure was less than 30 % the design value (Blanco-Fernandez et al, 2013).

In addition, numerical modelling confirmed that the confining effect by the membrane on the ground is limited as long as there is no layer failure (Pol et al, 2020; Pol and Gabrieli, 2021). This is related to the fact that the mechanical response of membrane panels to out-of-plane loading is first very small and progressively increases with the membrane deflection (Fig. 6). It thus depends on the mechanical characteristics of the membrane. Based on their findings, these authors proposed that FFS should be considered as passive systems.

In the end, the active behaviour appears to be often debated, and would deserve further investigations.

6.1.3 LE approaches

The stabilising effect provided to the ground layer by the FFS is most often computed based on a LE approach which models the layer as a collection of rigid bodies. This implies that the membrane has an infinite stiffness and that it is initially prestressed, which latter condition implies an active behaviour.

The influence of the membrane stiffness on the system response has been evidenced by many authors. Based on experimental data concerning FFS in active conditions and tested with the facility presented in Fig. 8, [Bucher et al \(2016\)](#) observed a lower deformation with a larger wire diameter, all else being equal. This confirms that neglecting the membrane stiffness as in a LE-approach-based design may lead to erroneous FFS design, even when the active condition is fulfilled. Numerical simulations conducted by [Blanco-Fernandez et al \(2016\)](#) confirmed that the membrane stiffness has a significant influence on the system response, and in particular on the confining stress applied by the membrane on the unstable layer, and that LE approaches tend to overestimate the confining effect when the membranes stiffness is low. [Pol et al \(2020\)](#) confirmed that neglecting the membrane stiffness was not appropriate for modelling 3D systems subjected to substantial displacements.

Last, LE approaches consider rigid bodies, from the layer surface to a sliding plane considered parallel to the layer surface. This assumption is questioned by results from ([Pol and Gabrieli, 2021](#)) which suggest that failure doesn't interest the entire layer thickness.

6.2 Recently proposed approaches

Main limitations with current design methods have been shown to concern the way the interaction between the ground layer and the FFS is accounted for. These limitations in particular relate to the active behaviour assumption, the consideration given to the membrane mechanical characteristics and the 3D nature of the problem. Recent research have been conducted to better model the loading experienced by the FFS and, conversely, the stabilising/confining effect on the ground layer. It led to the development of displacement-based FFS design methods (in an hybrid design perspective) relying on so-called characteristic curves ([Galli and di Prisco, 2013](#); [Galli et al, 2020](#); [Maccaferri, 2021a,b](#); [Boschi et al, 2023](#)). Basically, these approaches relate the

soil displacement to the stabilising effect by the membrane. Undoubtedly, this constitutes a significant step forward and a promising way for circumventing most of the limitations in analytical models proposed up to now. It allows moving to a proper force-displacement design as suggested by [Blanco-Fernandez et al \(2016\)](#); [Pol et al \(2020\)](#); [Pol and Gabrieli \(2021\)](#).

Characteristics curves aim at reflecting the evolving interaction between the unstable layer and the FFS. These curves provide the reaction force of a nail plate pressed onto a membrane covering a soil layer, as illustrated in Fig. 7. Such curves may be obtained from experiments or from numerical simulations ([di Prisco et al, 2010](#); [Gabrieli and Pol, 2019](#); [Boschi et al, 2020](#); [Galli et al, 2020](#); [Boschi et al, 2021](#); [Pol and Gabrieli, 2022](#); [Boschi et al, 2023](#)). With respect to the application case, these curves provide the force opposed by the plate and membrane to the progressive displacement of the ground. Such curves account for the complex interaction between the nail plate, the membrane and the soil ([di Prisco et al, 2010](#); [Gabrieli and Pol, 2019](#); [Boschi et al, 2020, 2021](#); [Pol et al, 2021b](#); [Pol and Gabrieli, 2022](#)) and may consider any nail plate size, membrane mechanical characteristics and soil characteristics, in a 3D context.

A FFS design approach accounting for such characteristic curves has been recently proposed ([Maccaferri, 2021a,b](#)). This method is exemplified in [Galli et al \(2020\)](#), considering a rectangular nailing pattern and addressing the soil layer instability with analytical models #8 and #9 (see Table 1). The reaction force by the FFS is applied on the lower block, which is located just above the nail. The reaction force is derived from the characteristic curve corresponding to the considered membrane and nail plate and accounting for the progressive block displacement. This design approach may be considered as a quasi 3D approach, in particular for what concerns the interaction between the ground layer and the FFS. The first main limitation in this global design approach seems to be related to the analytical model used for addressing the ground

layer instability (2D and two-blocks failure mechanisms). In addition, a rigorous implementation of the proposed approach would require a large number of characteristic curves (considering various soils, membranes and nail plates). By contrast, the available information concerning these characteristic curves and the way they were obtained is rather limited till now (di Prisco et al, 2010; Boschi et al, 2020, 2021). Nevertheless, these recently proposed approaches are extremely promising.

7 On the best design criterion

Up to now, the deformation of the membrane was generally considered as the main design criterion : the lower the deflection, the better the design. In a broader perspective, the cost efficiency of FFS could be given a higher importance. Main costs associated with FFS being related to nailing operations (drilling...), reducing the number and/or length of nails could be a possible design improvement track. This optimisation process could lead to reconsider the nailing pattern, nail spacing and the addition of reinforcement ropes. Marchelli and Giacchetti (2021) have suggested that improving the reinforcement ropes layout could result in global cost reduction. One of the reasons is that reinforcement ropes enable better stress distribution within the membrane and reduce the loads on the membrane in the nail plate vicinity.

In such an optimisation process, a particular attention should be paid to both the loads transmitted to the nails and to membrane punching in the nail plate vicinity where membrane failure occurs. In fact, these constitute the most important design criteria. It is worth mentioning that data related to the force transmitted to the nails are presented in a very limited number of documents (Muhunthan et al, 2005; Sasiharan et al, 2006; Justo et al, 2014).

As for the nailing pattern, some works have suggested that a rectangular pattern is advantageous over a rhomboidal one for membranes with a rhomboidal mesh (Xu et al, 2019). This goes against the general trend observed since the end of the 90's.

Indeed, the rectangular pattern was preferred before the introduction of membranes with a rhomboidal mesh (Bucher et al, 2016; Fonseca and Dias Trillos, 2020), which led to prefer the rhomboidal pattern. In addition, the rhomboid nailing pattern has the apparent advantage of offering more obstacles to the sliding of ground layer slices (due to the fact that nails are staggered from one row to the other). Such an improvement in favor of a rectangular pattern could take advantage of the interpretation of Fig. 13 where the 'line' between two nails corresponds to a sector where a high confining pressure is applied by the membrane on the ground. The displacement of the ground below this line is much restricted than anywhere else below the membrane panel (except below the nail plates). The confined ground volume, along this line, acts as a buttress for the rest of the ground layer. This effect is similar to that observed in the vicinity of the nails, which influence is concentrated. The relative influence of these two stabilising mechanisms could be investigated, to evaluate to which extent, in the case of a mesh with a rhomboidal pattern, it is relevant to consider a rhomboidal nailing pattern compared to a rectangular one and considering other structural arrangements (ropes between nails for example).

8 Conclusion

This article deals with the design of flexible facing systems used for the stabilisation of ground layers on slopes. These systems have been used successfully for decades and their design is generally based on analytical models that deal with stability using limit equilibrium approaches and treating the problem in two dimensions. A reading of the available literature reveals that the response of membranes to out-of-plane loading applied by a given unstable soil layer depends on many parameters related to the characteristics of the membrane as well as the geometry and spacing of the nailing pattern. The limitations of the test methods prescribed to characterise the membranes to be used for these applications were highlighted, as were those of the numerical models.

The relevance of the analytical methods currently used was discussed, suggesting that these methods should be progressively supplemented or replaced by other approaches with a view to improving FFS design.

Although recent research has led to significant advances in terms of knowledge and design methods, there is still room for improvement. From an academic point of view, the general questions that remain concern the load that the unstable soil layer applies to the membrane, which in turn deforms, and how the loads pass through the membrane to the nails. There is no doubt that these issues are extremely complex to deal with, given the dependence of the mechanisms involved on the various parameters describing the system as a whole, including the ground layer. From a more practical point of view, improving the design of flexible facing systems on the basis of global-cost-effectiveness seems to be a challenging and exciting issue for academics, engineers and manufacturers.

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Competing interests

The authors declare no competing interests.

9 Author Contributions

All authors equally contributed to the writing of this article, from the first draft to the submitted version.

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